7.6 OPTIMIZATION OF WEATHER UPDATE TIME AND DATA QUALITY USING PHASED-ARRAY RADAR

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1. Introduction

The Weather Surveillance Radar-1988 Doppler (WSR-88D) has proven to be a vital instrument for meteorological and climatological applications. It has been shown that the warning lead time for severe weather has been significantly improved after the installation of the national network of WSR-88Ds (Polger et al. 1994). The current WSR-88D system completes a volume coverage pattern (VCP) in a minimum of approximately 4 min for 14 elevation steps (Lee and Steadham 2004). For radar with a mechanically rotating antenna, long dwell times are often needed to acquire a sufficient number of independent samples, because successive signals in sample time are highly correlated. However, rapid scanning is needed not only to increase the warning lead time but also to advance the understanding of fast-evolving weather systems. An intuitive way to reduce the data acquisition time for a given VCP or a sector scan is to increase the antenna rotation rate. As a result, the statistical error of the three spectral moments (reflectivity, mean Doppler velocity, and spectrum width) will increase due to a decrease in the number of samples for processing. Moreover, the rotational rate is constrained by the mechanical limitation of a pedestal. In this work, a novel scanning strategy is developed to directly collect independent samples (Zrnić 1977). During the time waiting for signals to become uncorrelated, the radar is tasked to probe other regions to maximize the usage of the radar resources as suggested in Smith et al. (1974). Hence, the radar beam is multiplexed over a designated region to provide measurements with low statistical errors in a relatively short period of time. This approach is termed beam multiplexing (BMX). To implement BMX, the radar beam needs to be steered rapidly from one location to another and for such a task, an electronically steered phased array radar is an ideal candidate. The S-band Phased Array Radar (PAR) was recently installed at the National Weather Radar Testbed (NWRT) in Norman, Oklahoma. The PAR initiative was developed through a unique research partnership including the Navy, federal agencies, private sectors, and university (Forsyth et al. 2001, 2002). The PAR is a national asset and has become available to research communities since September, 2003 (Forsyth et al. 2005). The PAR is equipped with a military SPY-1A antenna from the Navy which allows electronic scanning in both azimuth and elevation on a pulse-to-pulse basis. Preliminary results have shown that the PAR can provide meteorological information which is consistent with those obtained by a nearby WSR-88D (Forsyth et al. 2005).

2. Beam multiplexing scanning strategy

BMX is developed to exploit the idea of independent pair sampling (IPS) (Zrnić 1977) and to make a full use of the radar. During the revisit time, the radar beam will be rapidly steered within the region of interest to collect independent pairs of samples at many beam locations. As a result, the data quality and acquisition time can be optimized. In designing the BMX scanning strategy, two fundamental issues need to be addressed. First of all, the revisit time T should be large enough to ensure the collection of independent pairs. At the same time, T should be small enough such that the weather of interest does not change significantly over the dwell time of LT, where L is the number of pairs. In other words, the $2L$ weather samples are collected from a stationary process with the same statisti-

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*Corresponding Author: T.-Y. Yu (tyu@ou.edu), School of Electrical and Computer Engineering, University of Oklahoma, Norman, OK 73019, USA cal properties. The decorrelation time of weather signal is defined by the time when the correlation coefficient has decreased by two orders of magnitude. For example, for an S-band radar, the revisit time should be larger than 24.2 ms for spectrum widths equal and larger than 1 m s^{-1}. The second issue is that the angular separation between any two consecutive beam locations should be large enough to suppress the second-trip echoes from previous beam location. If two locations are too close, the data collected in the current location will be contaminated by the second-trip echo from the previous beam location through large sidelobes or even the mainlobe. Therefore, BMX requires a radar to steer the beam from one location to another one, which should be a few degrees apart, every couple PRTs. This is different from the conventional scanning strategy, in which the beam location varies continuously due to the mechanical rotation of the antenna. Thus, a phased array radar is an ideal instrument for implementing BMX due to its fast and flexible beam steering.

It is of interest to quantify the gain in data acquisition time using BMX while the estimation accuracy obtained by a continuous pair sampling (CPS)-based scanning strategy is maintained. Therefore, the improvement factor of data acquisition time, which is defined by the ratio of T_{A_C}/T_{A_I}, can be derived by equating the variance from IPS and CPS and then solving for $M/(2L)$, where M is the number of samples collected using CPS, T_{A_C} and T_{A_I} are data acquisition time of a sector scan with n_b radials using CPS and IPS, respectively . As a result, the improvement factor derived from the signal power (I_S) and mean velocity (I_v) estimates for a large number of samples can be obtained theoretically. The improvement factors of acquisition time as a function of normalized spectrum width are shown in Figure 1 for SNR=20, 5, and 0 dB. If I_S and I_v are smaller than one, no gain in acquisition time will be obtained by BMX. For the case of signal power, the improvement is more significant at smaller spectrum widths for all SNRs. This is because signals are more correlated and consequently, more samples are needed in CPS to achieve the required accuracy of power estimates. Moreover, I_v is larger than unity when spectrum width is small and the SNR is relatively high. The reason is that the noise from the common pulse of adjacent pairs in CPS will be canceled in the averaging process (Zrnić 1977). Thus, the required performance of velocity estimator can be obtained by CPS with a fewer samples at low SNR. It is evident that the most favorable conditions for BMX are small spectrum width and large SNR for both cases. For weather application, the SNR is often reasonably high and the median spectrum width ranges approximately from 1-5 m $s^{-1}$for various types of weather phenomena (Fang et al. 2004).

3. Experimental Results

An experiment was conducted to demonstrate and verify BMX on May 2, 2005. A 28° sector from azimuth 183° to 156° was scanned using two scanning strategies. The 28° sector was first scanned using BMX with two 14° sectors. In each sector, the PAR was beam multiplexed over 14 beam positions, where 32 pairs of pulses were collected at each beam position. As a result, the acquisition time of BMX is 1.792 s with a PRT of 1 ms. The other scanning strategy is a step scan (SS) which was devised to probe the same 28° sector with 28 discrete beam positions. Data from 64 pulses were collected before the beam was steered to the next azimuth location. These azimuthal locations are one degree apart. It is similar to the conventional scanning strategy used in weather radar with a mechanically rotating antenna. But the SS will not produce spectral broadening effect (Doviak and Zrnić 1993) because the antenna is stationary. Note that a direct demonstration of improvement factor is not possible without a-priori knowledge of spectrum width and SNR. Therefore to make a comparison, data acquisition time of BMX is set to be same as SS (i.e., $M = 2L$). If the standard deviations of power and velocity estimates from BMX are smaller than those from CPS, it indicates that the improvement in acquisition time could be obtained using BMX when the estimation accuracy is the same as CPS. Moreover, to perform statistical analysis, the two scanning strategies were alternated 50 times.

Statistical results at azimuth 159° are selected to exemplify the performance of BMX and SS because of a large region of high SNR. The mean and SD of the three spectral moments were estimated from T_2 (i.e., from the 17th scan to the 32nd scan in each strategy). Statistical results from other time periods are similar. Note that a linear trend in the moment estimates was removed, if it existed, before the calculation of SDs. The procedure is performed in an attempt to remove the non-homogeneous portion of the estimates. The mean profile of the reflectivity, radial velocity, and spectrum width is shown in Figure 2. The results of BMX are denoted by solid lines while the results of SS are indicated by dashed lines. It is evident that

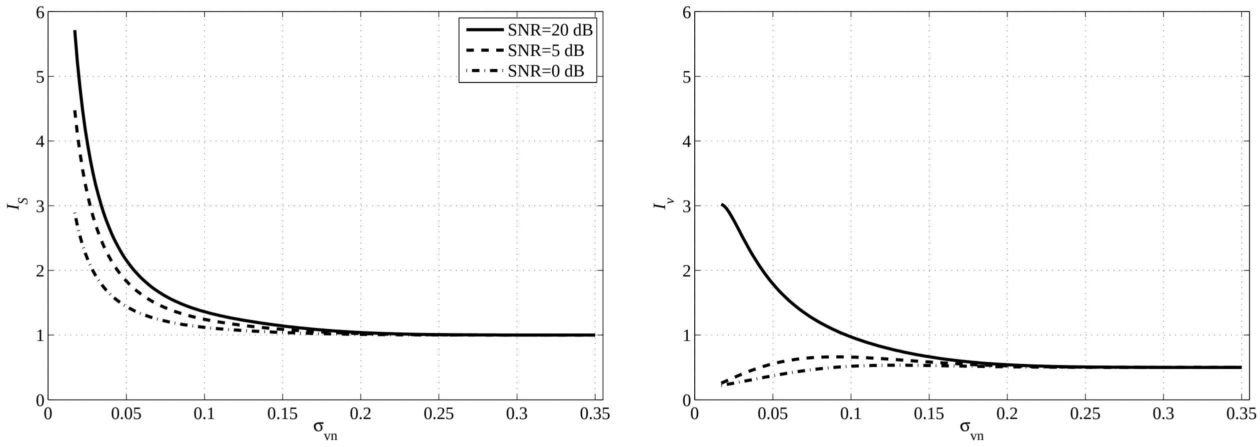


Figure 1: The improvement factor for (a) signal power estimate and (b) mean velocity estimate as a function of normalized spectrum width at SNR=20, 5, and 0 dB.

the means of three spectral moments estimated from both scanning strategies are extremely similar. The difference in reflectivity, radial velocity, and spectrum width between BMX and SS and averaged over entire ranges is 0.05 dBZ, 0.003 m s^{-1}, and 0.08 m s^{-1}, respectively. The SD of reflectivity and mean velocity from both scanning strategies is shown in Figure 3. The mean SNR from BMX over the same 16 realizations is superimposed and is denoted by black lines. The value of SNR is referred to the vertical axis on the right. The SD of BMX reflectivity and velocity is denoted by red lines, while the SD of reflectivity and velocity from SS is denoted by blue lines. It is evident that BMX can provide more accurate reflectivity and velocity estimates up to approximately 90 km, where the SNR is larger than 10 dB and the mean spectrum width is 1-2 m s^{-1}(as shown in Figure 2c). In other words, the results indicate that the data acquisition time can be reduced by BMX while maintaining the same accuracy as in the SS. To further verify the theoretical relations discussed in section 2.a, the mean SNR and spectrum width were fitted to obtain theoretically fitted SDs for BMX. The resultant SD of reflectivity is denoted by the green line. Similarly, the theoretically fitted SD of reflectivity for SS can be obtained and is denoted by the cyan line. It is evident that the fitted SD of reflectivity agrees reasonably well with the observational results for both BMX and SS if the SNR is higher than approximately 5 dB. The discrepancy between fitted and observational SDs beyond 120 km may be caused by inaccurate estimation of spectrum width in the autocovariance method at low SNR. Furthermore, the fitted SDs of velocity for both BMX and SS are also consistent with the SDs measured directly from observations between 20 km and 95 km. However, a discrepancy in SS velocity estimates between 40 km and 60 km is observed. The reflectivity in this region decreases with a constant rate of approximately 0.08 dB/sec. A possible reason for the discrepancy can be that the high reflectivity structure is not homogeneous within the radar volume.

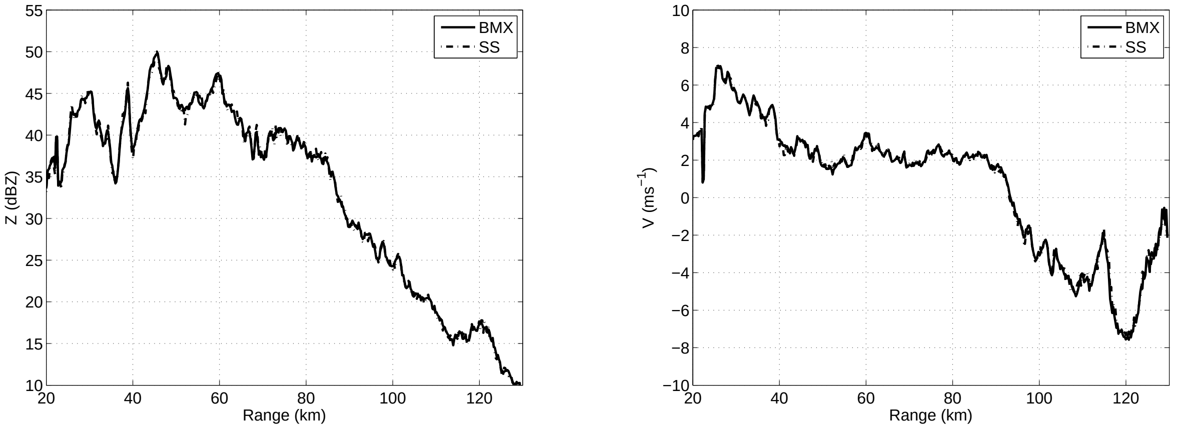
The improvement factor of acquisition time is defined such that the same SD is achieved for both BMX and SS. In this experiment with the same acquisition time, the reduction in SD using BMX can be translated into the improvement factor. In other words, the improvement factors I_s and I_v can be obtained by the ratio of $\mathrm{V}ar\{\hat{S}_C\}/\mathrm{V}ar\{\hat{S}_I\}$ and $\mathrm{V}ar\{\hat{v}_C\}/\mathrm{V}ar\{\hat{v}_I\}$, respectively. The minimum of I_s and I_v at each range gate is used to represent the overall improvement factor since both signal power and velocity estimates are of interest. Moreover, the mean improvement factor at each radial is obtained by averaging data whose SNR is larger than 10 dB over the entire ranges. The resultant measure of performance is shown in Figure 4 for the three time periods. The improvement factors from the three time periods are consistent. It is clear that the data acquisition time can be improved by an average factor of 2-3.8 in this case. Note that the first few radials are associated with high reflectivity regions and, hence estimates therein can be improved more significantly than elsewhere.

4. Conclusions

A fundamental limitation of rapid scans using a mechanically rotating antenna is the degradation

(a) Mean Reflectivity

(b) Mean Velocity



(c) Mean Spectrum width

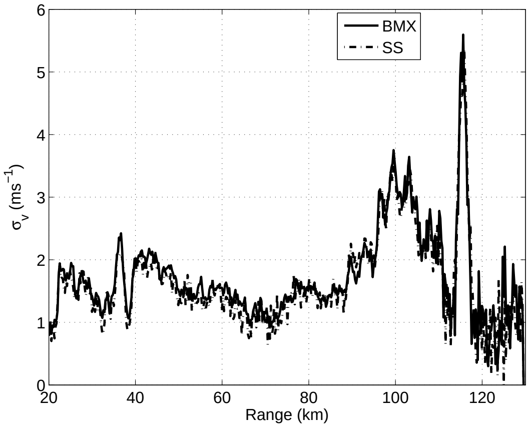


Figure 2: Mean profile of (a) reflectivity, (b) velocity, and (c) spectrum width at azimuth of 159° .

of data quality. In this work, a novel scanning strategy which exploits the collection of independent radar samples and maximizes the radar resources is developed. It is termed beam multiplexing (BMX) whereby the radar beam is multiplexed to provide optimal data quality and acquisition time. Two criteria for designing BMX are provided and discussed. The improvement factor of acquisition time is theoretically derived for the cases of signal power and mean velocity estimates. It has been demonstrated that the acquisition time can be reduced significantly especially at small spectrum widths and high SNR. The improvement in data acquisition time with an average factor of 2 to 4 were obtained from the data. Note that additional decrease in scan time can be achieved if more antenna faces are used. Although BMX is not favorable when the spectrum width is large and/or SNR is relatively low, especially for the case of mean velocity estimates, the PAR has the potential to adaptively switch to a mode of SS to provide optimal scanning strategy.

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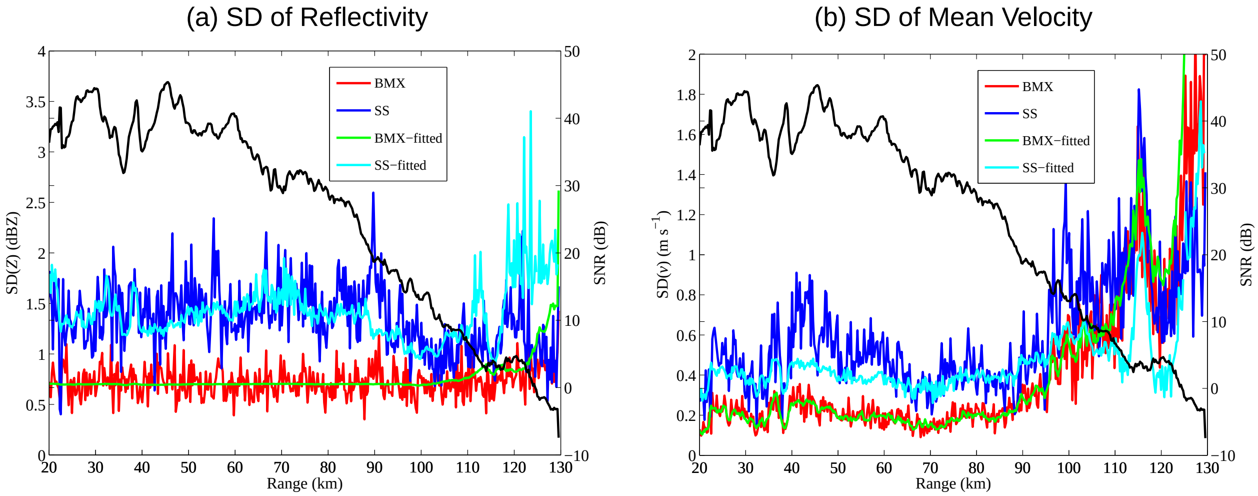
(a) SD of Reflectivity

(b) SD of Mean Velocity

Figure 3: The SD of (a) reflectivity and (b) mean velocity estimates at azimuth of 159° . The mean SNR is denoted by black line. Moreover, the theoretically fitted SDs are superimposed.

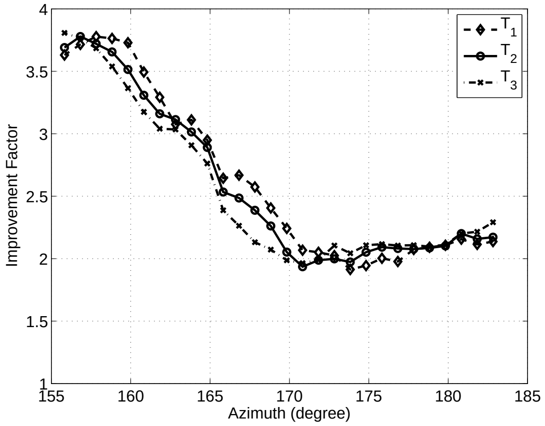

Figure 4: Averaged improvement factor of acquisition time at 28 radials based on theoretically fitted SDs. An improvement factor of 2 to 3.8 was obtained during the experiment.

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